ESTABLISHING TRADE-OFFS BETWEEN SUSTAINED AND MOMENTARY RELIABILITY INDICES IN ELECTRIC DISTRIBUTION PROTECTION DESIGN: A GOAL PROGRAMMING APPROACH

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Abstract – In this paper, electric distribution reliability is considered under both aspects of customer interruptions: sustained and momentary. A contingency simulation-based technique is used to develop nonlinear models for the SAIFI and MAIFI reliability indices, taking into account the protective devices locations and reclosing schemes used in the substation breaker and line reclosers. The models are aggregated to a set of linear constraints to constitute a nonlinear goal programming model, used to establish the tradeoff between SAIFI and MAIFI reliability indices. As a result, the methodology enables deterministic optimization of distribution feeder protection design by identifying types and locations for protective devices, and the protection schemes to be employed in the line reclosers and substation breaker: fuse saving or fuse blowing. A case study considering a real distribution feeder with 51 buses is presented to illustrate the application and evaluate the performance of the proposed optimization methodology.

Keywords: Power distribution reliability, power distribution protection, distribution reliability indices, goal programming.

1 INTRODUCTION

Overcurrent protection system design has direct impact on electric distribution reliability. Traditionally, procedures for protective devices utilization vary according to the reliability rules developed by electric energy companies [1]. Since the inception of the electric power industry, the utilities protection practices have focused on reducing the frequency of sustained interruptions [2]. Reliability indices such as SAIFI (System Average Interruption Frequency Index) have been commonly used by utilities and regulatory agencies to evaluate the system performance and establish service continuity criteria.

Today, the increasing sensitivity of customer loads to brief disturbances has forced the utilities to find ways to reduce the number of momentary interruptions that occur on their systems [3]. This has resulted in increasing popularity of the associated indices, such as MAIFI (Momentary Average Interruption Frequency Index) [4]. Distribution protection system design must now consider the impact of momentary in addition to the permanent interruptions.

The systematic selection and allocation of protective devices allows limiting the effect of faults on the distribution feeder, minimizing the number of customers affected by protective device operation and, thereby, minimizing the feeder reliability indices [1, 5]. This applies not only to the sustained interruptions-related reliability indices used by the utility industry, but also a reduction in momentary reliability indices [2]. Additionally, reclosing schemes have a substantial impact on reliability indices, and utilities must consider them in the design of the feeder protection system [3].

Some papers are found in the literature addressing deterministic optimization of reliability, by identifying types and locations of protective devices in distribution systems. Ref. [6] presented the first linear binary programming (LBP) model in order to minimize the SAIFI index. To simplify the model, the formulation defines the division of the distribution feeder in one main feeder and laterals, which were heuristically classified in one of three categories. The shortcoming of the model is that it does not consider the effects of failures between the main feeder and the laterals, which can lead to suboptimal solutions [1], [5], [7]. Additionally, the model requires that the main feeder and laterals do not have branches, which must be subsumed at the tap points, resulting in the loss of information about the feeder topology. In [8], the authors present a similar model to [6], to minimize the cost of protective devices acquisition, subject to reliability constraints. Also based in [6], [4] presented a goal programming technique in order to find the trade-off between the SAIFI and ASIFI (Average System Interruption Frequency Index) indices. From the solution obtained are selected the reclosers where a fuse saving scheme should be applied, based on the trade-offs between a decrease in the SAIFI index and an increase in the MAIFI.

In [5] and [9] nonlinear binary programming (NLBP) models are presented to minimize the total cost of reliability. Similar to [6], the authors employ the division of distribution feeder in one main feeder and laterals, which cannot have branches. Ref. [1] presented an improved NLBP model compared to [6], in order to minimize the SAIFI index of a feeder. Although using the same form of feeder division of [6], the model takes into account the effects of failures between the main feeder and the laterals. Finally, in [7] a more generalized NLBP model is presented to minimize the SAIFI or SAIDI index. By departing from the feeder division adopted in the models previously presented, the model can represent with more fidelity the interactions between the protective devices, resulting in a more accurate model for the SAIFI index.

Except for [4], all the approaches previously presented are single objective models that address the optimization of reliability indices or economic costs, taking into account just the impact of sustained interruptions. In this paper, distribution reliability is considered under both aspects of customer interruptions: sustained and momentary. A contingency simulation-based technique is used in the SAIFI and MAIFI models formulation, to accurately reproduce the protection system response to faults according to the protective devices locations and reclosing schemes used in the substation breaker and line reclosers. The nonlinear models are aggregated to a set of linear constraints, and the resultant NLBP models are independently solved. The numerical results (lower bounds of the indices) are then stated as goals to a nonlinear goal programming (NLGP) model, used to establish the trade-off between SAIFI and MAIFI reliability indices. As a result, the methodology enables deterministic optimization of distribution feeder protection design by identifying types and locations for protective devices, and the protection schemes to be employed in the reclosers and substation breaker: fuse saving or fuse blowing. A case study considering a real distribution feeder with 51 buses is presented to illustrate the application and evaluate the performance of the proposed optimization methodology.

2 PROBLEM FORMULATION

2.1 Distribution Feeder Topology Model

Fig. 1 shows the one-line diagram of a radial distribution feeder, consisting of main feeder and lateral branches. The feeder is divided in sections arbitrarily numbered, each one corresponding to a candidate point for the placement of protective devices. The installation of a device in a section is defined as being at the beginning of that section. For the purposes of this paper, interconnection points (tie points) with adjacent feeders or alternative sources are not considered. The distribution feeder can be represented by a tree graph, where nodes represent tap connections or load points. Since each edge has a unique end node in the tree graph, the system can be represented in terms of edges, or feeder sections. The feeder topology modeling is based on sets, which composition process is defined as follows: let G be the set of edges of the tree graph that represents the distribution feeder, and $p(i)$ be the immediate predecessor of edge i on set G. Set U_i is defined by (1):

$$U_i = \left\{ i,\, p(i),\, p\left(p(i)\right),\, p\left(p\left(p(i)\right)\right), \dots,\, 1 \right\}. \qquad (1)$$

Set U_i contains section i and all the feeder sections that precede i (upstream i) to section 1, which by definition, is the substation. For example, considering Figure 1: $U_1 = \{1\}$, $U_4 = \{1, 3, 4\}$, and $U_7 = \{1, 3, 6, 7\}$.

2.2 Faults and Interruptions

The faults that occur in distribution systems can be classified as temporary or permanent. A temporary fault will clear up if de-energized and then re-energized, and a permanent fault will persist until repaired by human intervention [10]. An interruption is the loss of service (power supply) to one or more customers, and is classified as momentary or sustained. Despite the use of the term momentary interruption, in this work will be considered the concept of momentary interruption event. A momentary interruption event is one or more interruptions of total duration limited to the time period of 5 minutes. A sustained interruption is any interruption not classified as a part of a momentary event [11].

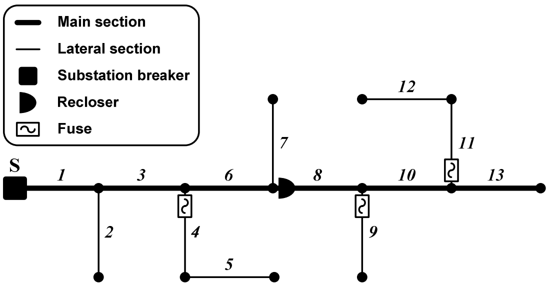

Figure 1: One-line diagram of a radial distribution feeder.

2.3 Distribution Feeder Overcurrent Protection

In this section the most relevant aspects of feeder overcurrent protection considered in the problem formulation are described. In general, protection of a distribution system consists of a circuit breaker with overcurrent relays and an automatic reclosing relay at the substation, and line reclosers and fuses placed at strategic points along the feeder. Sectionalizers are also used, but they will not be considered in this paper. Due to their operational similarities, substation breaker and relays can be represented as a recloser allocated in the first feeder section.

The recloser has fault current interrupting and automatic reclosing capabilities, operating with a predetermined sequence of opening and reclosing followed by its lockout. The fuse does not have automatic reclosing capability. It can only perform open-circuit function, separating the faulted circuit by melting its fuse-link. Hence, the fuse is not able to clear the momentary faults by itself.

Two basic reclosing practices are commonly used in recloser-fuse coordination: fuse saving and fuse blowing. Fuse saving (also referred to as feeder selective relaying) is usually implemented with the fast curve on a recloser (or the instantaneous relay on a breaker) so that the recloser (or breaker) operates before the downstream lateral fuses for faults on the laterals. For a temporary fault in a fused lateral, all customers downstream the recloser experience a momentary interruption. If the fault is permanent, customers downstream the recloser experience a momentary interruption and customers downstream the fuse experience a sustained interruption. Fuse saving scheme results in fewer sustained interruptions, but more momentary interruptions. In the fuse blowing (or fuse clearing) scheme, the fast curve of recloser (or the breaker instantaneous relay) is blocked. The fuse operates for both temporary and permanent faults, with the customers downstream the fuse experiencing a sustained interruption, and the rest of the feeder is prevented from experiencing an interruption. This results in fewer momentary interruptions but more sustained interruptions.

In this paper, we use the terminology fuse saving recloser and fuse blowing recloser, in references to the breaker and reclosers operating under the fuse saving and fuse blowing reclosing schemes, respectively.

3 PROPOSED METHOLOGY

3.1 SAIFI and MAIFI Models

In this paper a contingency simulation-based technique is used in the SAIFI and MAIFI models formulation to accurately reproduce the protection system response to faults. The following assumptions must be considered in the models formulation: 1) the failures are independent and mutually exclusive; 2) the protective devices are perfectly coordinated; 3) the failure rates of protective devices are neglected; and 4) the feeder is operated as a radial feeder.

The binary decision vectors indicating the feeder sections where fuse saving reclosers, fuse blowing reclosers, and fuses are installed are defined according to (2):

$$x_j = \begin{cases} 0, & \text{if a fuse saving recloser is installed} \\ & \text{on section } j. \\ 1, & \text{otherwise.} \end{cases}$$

$$y_j = \begin{cases} 0, & \text{if a fuse blowing recloser is installed} \\ & \text{on section } j. \\ 1, & \text{otherwise.} \end{cases} \tag{2}$$

$$z_j = \begin{cases} 0, & \text{if a fuse is installed on section } j. \\ 1, & \text{otherwise.} \end{cases}$$

$$x_j \in \mathbf{x}, \quad y_j \in \mathbf{y}, \quad z_j \in \mathbf{z}, \quad j = 1 \ldots |G|.$$

Where the vertical bars denote the cardinality (number of elements) of set G.

SAIFI is the most used index by electric utilities to evaluate the frequency of sustained interruption in distribution systems [11]. Currently, MAIFI is becoming more prevalent because some public service commissions are requiring utilities to report information on momentary interruptions, and customers are complaining about shutdown of electronic loads [12].

As mentioned in Section 2.2, it is used the concept of momentary interruption event, whose index corresponds to the MAIFI_E (Momentary Average Interruption Event Frequency Index). For sake of notation, despite the use of the term MAIFI, this work has considered the MAIFI_E definition. SAIFI and MAIFI_E indices are formally defined in [11]. For a given feeder, the indices estimation can be calculated by (3) and (4), respectively.

$$SAIFI = \frac{\sum_{i \in G} I_i^S N_i}{N_T} \tag{3}$$

$$MAIFI = \frac{\sum_{i \in G} I_i^M N_i}{N_T} \tag{4}$$

Where G is the set of feeder sections, I_i^S and I_i^M are respectively, the expected number of sustained and momentary interruptions for section i, N_i is the number of customers within the boundaries of section i, and N_T is the total number of customers on the feeder.

Considering the SAIFI estimation as a function of decision vectors **x**, **y** and **z** defined in (2), the numerator of (3) is rewritten as:

$$SAIFI_{\mathbf{x},\mathbf{y},\mathbf{z}} = \Bigg(\sum_{i \in G} \lambda_i \sum_{j \in U_i} N_j \overline{x_j y_j z_j} \prod_{k \in (U_i - U_j)} x_k y_k z_k \tag{5}$$

$$+ \sum_{i \in G} \gamma_i \sum_{j \in U_i} N_j \overline{z_j} \prod_{k \in (U_i - U_j)} x_k y_k z_k \prod_{l \in U_j} x_l \Bigg).$$

Where:

λ_i and γ_i are the permanent and temporary failure rates of section i [failures/km.year];

N_j is the total number of customers downstream section j, including customers in section j;

$U_i - U_j$ is the complement of U_i in U_j, and results in a set formed by the elements of U_i that are not elements of U_j.

Equation (5) evaluates the expected annual frequency of sustained interruptions of a feeder, given the locations of fuse saving reclosers, fuse blowing reclosers and fuses. The first term of (5) corresponds to the impact of permanent faults in section i when a recloser or fuse is installed in section j, upstream to section i, and there is not a recloser or fuse installed in sections k, between sections i and j. In this case, the protective device in section j (the first device upstream the faulted section i) operates to clear the fault in section i, and customers downstream section j (j included) experience a sustained interruption. The second term of (5) represents the impact of temporary faults in section i when a fuse is installed in section j, there is no other device in sections k, and there is not a fuse saving recloser in sections l, upstream the fuse. If $i = j$ then $U_i - U_j = \varnothing$ (empty set). Since 1 is the neutral element of multiplication, we define the product operators over empty sets equal to 1. In the same manner, since 0 is the neutral element of addition, the sum over empty sets is defined as equal to 0.

The opposite value complements of the decision variables in (5) are expressed by (6) and (7):

$$\overline{x_j y_j z_j} = 3 - x_j - y_j - z_j \tag{6}$$

$$\overline{z_j} = 1 - z_j \tag{7}$$

Replacing (6), (7) and grouping the first and second terms of (5), its final form is expressed by (8):

$$SAIFI_{\mathbf{x},\mathbf{y},\mathbf{z}} = \sum_{i \in G} \sum_{j \in U_i} N_j \Big[\lambda_i \left(3 - x_j - y_j - z_j \right) \gamma_i \left(1 - z_j \right) \prod_{l \in U_j} x_l \Big] \prod_{k \in \left(U_i - U_j \right)} x_k y_k z_k . \tag{8}$$

The numerator of (4) is rewritten as (9), to express the proposed MAIFI estimation as a function of decision vectors **x**, **y** and **z**:

$$\begin{aligned} MAIFI_{\mathbf{x},\mathbf{y},\mathbf{z}} = & \sum_{i \in G} \gamma_i \sum_{j \in U_i} N_j \overline{x_j} \prod_{k \in \left(U_i - U_j \right)} x_k \\ & + \sum_{i \in G} \gamma_i \sum_{j \in U_i} N_j \overline{y_j} \prod_{k \in \left(U_i - U_j \right)} x_k y_k z_k \prod_{l \in U_j} x_l \\ & + \sum_{i \in G} \lambda_i \sum_{j \in U_i} N_j \overline{x_j} \prod_{k \in \left(U_i - U_j \right)} x_k \left(1 - \prod_{l \in \left(U_i - U_j \right)} z_l \right) \\ & - \sum_{i \in G} \lambda_i \sum_{j \in U_i} N_j \overline{z_j} \prod_{k \in \left(U_i - U_j \right)} x_k y_k z_k \left(1 - \prod_{l \in U_j} x_l \right). \end{aligned} \tag{9}$$

Equation (9) evaluates the expected annual frequency of momentary interruptions events of a feeder. First and second terms represent the impact of temporary faults in a section *i*. The former represents the fault clearing by a fuse saving recloser installed in section *j* upstream faulted section *i*, and there is no other fuse saving recloser installed in sections *k*, between sections *i* and *j*. The second term represents the temporary fault clearing by a fuse blowing recloser installed in section *j*, when there is no other device in sections *k*, and there is not a fuse saving recloser upstream section *j*. The third and fourth terms of (9) represent the impact of permanent faults in a section *i* located downstream a fuse, when a fuse saving recloser is installed upstream the fuse. In this case, the customers between the recloser and the fuse experience a momentary interruption. The third term is active if there is a fuse saving recloser in section *j*, there is no other fuse saving recloser in sections *k* (between sections *i* and *j*), and there is a fuse installed in sections *l*, also between sections *i* and *j*. The forth term is active if a fuse is installed in section *j*, there is no other device in sections *k*, and there is a fuse saving recloser in sections *l*, upstream section *j*. Customers downstream the fuse (determined by the fourth term) will experience a sustained interruption, so they are subtracted from the customers downstream the fuse saving recloser (determined by the third term).

The following equations are used to eliminate the opposite value complements of the decision variables in (9):

$$\overline{x_j} = 1 - x_j \tag{10}$$

$$\overline{y_j} = 1 - y_j \tag{11}$$

By replacing (7), (10) and (11) and grouping the terms of (9), it yields:

$$\begin{aligned} & MAIFI_{\mathbf{x},\mathbf{y},\mathbf{z}} = \\ & \sum_{i \in G} \sum_{j \in U_i} N_j \Big\{ \Big[\Big(\left(\gamma_i + \lambda_i - \gamma_i y_j - \lambda_i z_j \right) \prod_{l \in U_j} x_l \\ & - \lambda_i \left(1 - z_j \right) \Big) \prod_{k \in \left(U_i - U_j \right)} y_k - \lambda_i \left(1 - x_j \right) \Big] \prod_{k \in \left(U_i - U_j \right)} z_k \\ & + \left(\lambda_i + \gamma_i \right) \left(1 - x_j \right) \Big\} \prod_{k \in \left(U_i - U_j \right)} x_k \end{aligned} \tag{12}$$

3.2 Constraints

A set of linear constraints is defined in this section to ensure the solutions feasibility from the NLGP model. Since the installation of a circuit breaker in the substation is mandatory, and fuses are not installed in the main feeder sections, constraints (13) and (14) must hold:

$$x_1 + y_1 = 1 \tag{13}$$

$$z_i = 1, \ \forall i \in Q \tag{14}$$

where Q is the set of main feeder sections.

In an attempt to ensure proper coordination of protective devices, the number of devices of the same type that can be installed in series is limited. In this paper, the number of reclosers and fuses placed in series is set in 3 at the most, according to (15) and (16):

$$\sum_{j \in U_i} x_j + y_j \geq 2 \left| U_i \right| - 3, \ \forall i \in G \tag{15}$$

$$\sum_{j \in U_i} z_j \geq \left| U_i \right| - 3, \ \forall i \in G \tag{16}$$

Economic limitations are considered by limiting the maximum number of reclosers and fuses available for the installation on the feeder, as expressed by (17) and (18):

$$\sum_{i \in G} x_i + y_i \geq 2 \left| G \right| - \left(nr + 1 \right) \tag{17}$$

$$\sum_{i \in G} z_i \geq \left| G \right| - nf , \tag{18}$$

Where nr and nf are the number of available reclosers (excluding the substation breaker) and fuses, respectively.

Finally, constraints (19) are added to ensure that no more than one device will be installed in each feeder section. Also, they ensure the validity of (6).

$$x_i + y_i + z_i \geq 2, \ \forall i \in G . \tag{19}$$

3.3 Goal Programming

Goal Programming (GP) is a multi-objective programming technique based on the concept of satisfying a number of objectives, trying to achieve a set of goals (or targets) as close as possible [13]. In the GP method used in this paper, the basic idea is that the decision maker specifies (optimistic) aspiration levels for the objective functions and the weighted sum of deviations from these aspiration levels is minimized. This is known as weighted GP (WGP). An objective function jointly with an aspiration level forms a goal. Aspiration levels are assumed to be selected so that they are not achievable simultaneously. The algebraic formulation of a WGP is given as [14]:

$$\begin{aligned}\min\ & \sum_{i=1}^{k} w_i^- \delta_i^- + w_i^+ \delta_i^+ \\ \text{s.t.}\quad & f_i(x) + \delta_i^- - \delta_i^+ = g_i, && \forall i = 1 \ldots k \\ & \delta_i^-, \delta_i^+ \geq 0_i, && \forall i = 1 \ldots k \\ & x \in C_s \end{aligned} \tag{20}$$

Where:

k is the number of objectives;

$f_i(x)$ is the achievement level of objective i;

g_i is the aspiration level for objective i;

δ_i^- and δ_i^+ are respectively the negative and positive deviations of $f_i(x)$ in relation to aspiration level g_i.

w_i^- and w_i^+ are weighting factors; and

C_s is the set of hard constraints.

In the proposed formulation, the two NLBP models constituted by (8), (12) and constraints (13-19) are solved independently to obtain the aspiration levels for the SAIFI and MAIFI indices. As they correspond to the lower bounds for the objectives, the negative deviations and associated weights in (20) can be eliminated.

Weights are selected to ensure appropriate tradeoffs between objectives and to perform an appropriate scaling of the deviational variables. The latter is important to overcome the unintentional bias towards the objectives with a larger magnitude (incommensurability) [13]. Weights in (20) are then redefined to normalize the deviational variables over the range between the maximum and minimum values of the aspiration levels:

$$w_i = \frac{w_i^+}{\left(g_i^{max} - g_i^{min}\right)}, \quad i = 1, 2. \tag{21}$$

By eliminating the negative deviations and weights, making $\delta_i = \delta_i^+$ (i = 1,2), and using (21), the WGP problem (20) is redefined to the scope of the proposed distribution reliability optimization problem as (22):

$$\begin{aligned}\min\ & w_1\delta_1 + w_2\delta_2 \\ \text{s.t.}\quad & SAIFI_{\mathbf{x},\mathbf{y},\mathbf{z}} - \delta_1 = g_1^{min} \\ & MAIFI_{\mathbf{x},\mathbf{y},\mathbf{z}} - \delta_2 = g_2^{min} \\ & \delta_1, \delta_2 \geq 0 \\ & \mathbf{x}, \mathbf{y}, \mathbf{z} \in C_s \end{aligned} \tag{22}$$

Now, the set of hard constraints C_s comprises the constraints defined by (13-19).

4 CASE STUDY

The proposed methodology was implemented in MATLAB environment [15]. The application receives as inputs the required feeder topology and reliability data and returns the SAIFI and MAIFI NLBP models, as well as the NLGP model (22), both in the General Algebraic Modeling System (GAMS) representation [16]. GAMS is a high-level language for mathematical programming problems, and serves as an interface to the Branch And Reduce Optimization Navigator (BARON) solver [17]. BARON implements deterministic algorithms of the branch-and-bound type enhanced with a variety of constraint propagation and duality techniques. The BARON solver can be used online, through the NEOS server for optimization [18].

The real distribution feeder shown in Figure 2 is used to illustrate the application and evaluate the performance of the proposed optimization methodology. The overhead three-wire distribution feeder has 51 sections, and serves 3958 customers with total load of 15871 kVA. Permanent (λ) and temporary failure rates (γ) in failures/km.year, and the number of customers (N) of each feeder section are listed in the Appendix. Originally, the feeder overcurrent protection system consists of a substation circuit breaker, 2 line reclosers and 18 fuses. We consider the circuit breaker and reclosers operating under the fuse blowing reclosing scheme.

The tests were performed considering the relocation of the existing protective devices. The first step is to solve the two NLBP problems of minimizing SAIFI and MAIFI indices to obtain the aspiration levels for the indices. The base case – which corresponds to the original locations of protective devices on the feeder – and the solutions obtained by minimizing SAIFI and MAIFI indices are shown in Table 1, where SAIFI is in interruptions per customer per year, and MAIFI is in momentary interruptions events per customer per year.

Case	**Sections**			**SAIFI**	**MAIFI**
	FBR	**FSR**	**Fuses**		
Base	1, 8, 39	–	4, 6, 10, 12, 16, 18, 20, 24, 27, 29, 34, 37, 40, 42, 44, 46, 48, 50	7.931	13.395
Min. SAIFI	–	1, 23, 38	4, 6, 8, 11, 12, 16, 18, 20, 24, 27, 32, 37, 39, 41, 44, 46, 48, 50	4.254	20.191
Min. MAIFI	1, 23, 31	–	4, 6, 8, 16, 18, 20, 24, 25, 27, 29, 32, 37, 39, 42, 44, 46, 48, 50	5.205	6.107

FBR = fuse blowing recloser, FSR = fuse saving recloser.

Table 1: Base case and solutions obtained by solving the SAIFI and MAIFI NLBP models.

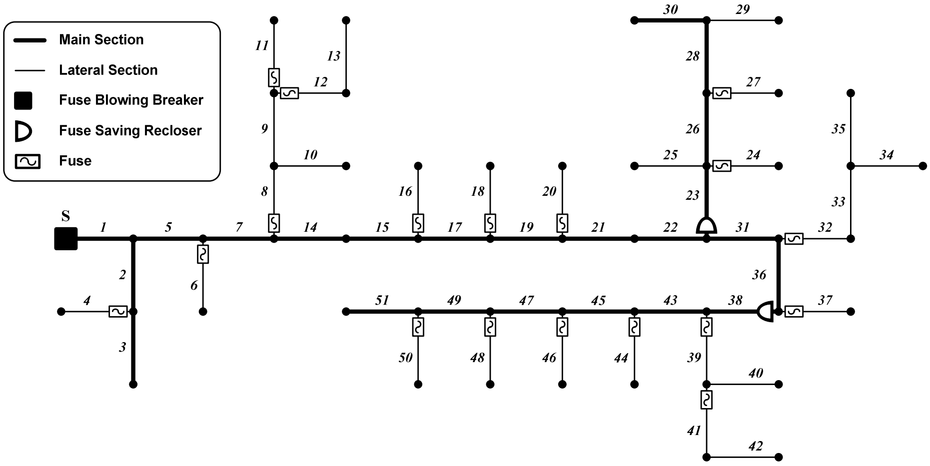

Figure 2: Overhead three-wire distribution feeder used in the case study with devices locations determined from the NLGP model for $w_1 = 0.6$ and $w_2 = 0.4$.

w_1	w_2	Sections			SAIFI	MAIFI
		FBR	**FSR**	**Fuses**		
0.1	0.9	1, 23, 31	–	4, 6, 8, 12, 16, 18, 20, 24, 27, 32, 37, 39, 40, 41, 44, 46, 48, 50	4.987	6.194
0.2	0.8	1, 31	23	4, 6, 8, 11, 12, 16, 18, 20, 24, 32, 37, 40, 41, 42, 44, 46, 48, 50	4.877	6.762
0.3	0.7	1	23, 43	4, 6, 8, 11, 12, 16, 18, 20, 24, 32, 37, 39, 40, 41, 44, 46, 48, 50	4.760	8.069
0.4	0.6	1	23, 38	4, 6, 8, 11, 12, 16, 18, 20, 24, 27, 32, 37, 40, 41, 44, 46, 48, 50	4.549	10.228
0.5	0.5	1	23, 36	4, 6, 8, 11, 12, 16, 18, 20, 24, 27, 32, 37, 40, 41, 44, 46, 48, 50	4.571	10.847
0.6	0.4	1	23, 38	4, 6, 8, 11, 12, 16, 18, 20, 24, 27, 32, 37, 39, 41, 44, 46, 48, 50	4.547	10.230
0.7	0.3	–	1, 23, 36	4, 6, 8, 11, 12, 16, 18, 20, 24, 27, 32, 37, 39, 41, 44, 46, 48, 50	4.286	19.718

FBR = fuse blowing recloser, FSR = fuse saving recloser.

Table 2: Solutions obtained from the proposed NLGP model with different weights.

From the NLBP models solutions, the aspiration levels for the SAIFI is g_1^{min} = 4.254 interruptions/customer.year, and for the MAIFI is g_2^{min} = 6.107 momentary interruptions events/customer.year. As the objectives of minimizing SAIFI and MAIFI are conflicting, the solution that minimizes an index will result in the maximum value for the other index. We consider these maximum values equal to the maximum values of the aspiration levels for the indices. Thus, g_1^{max} = 5.205 and g_2^{max} = 20.191 in Equation (21).

The second step is to find the optimal trade-off between the SAIFI and MAIFI indices. The goal is to find a solution that achieves the established goals as close as possible. Different solutions can be obtained by using different weights in (21), making it possible for the engineer or planner to select one of the solutions, which satisfies the objective functions based mostly on his or her professional point of view. Table 2 shows the set of solutions obtained from the proposed NLGP model, when weights are varied in steps of 0.1, such that $w_1 + w_2 = 1$. For w_1 greater than 0.7, the solutions are equal to the Min. SAIFI case. Then these solutions are excluded from Table 2. Figure 3 shows the graphical representation of the solutions from Table 2 with labels indicating the associated weights (w_1, w_2), as well as the solutions from the minimization of SAIFI and MAIFI indices. As it can be seen, the solution (0.5, 0.5) is dominated by solutions (0.6, 0.4) and (0.4, 0.6), indicating that no Pareto optimal solution is available in that region of solutions space. Protective devices locations determined by solution (0.6, 0.4) are shown in Figure 2. This solution indicates a possible reduction to 57.3% and 76.4% of the original SAIFI and MAIFI indices, with deviations of 6.9% and 67.5% from the established aspiration levels, respectively.

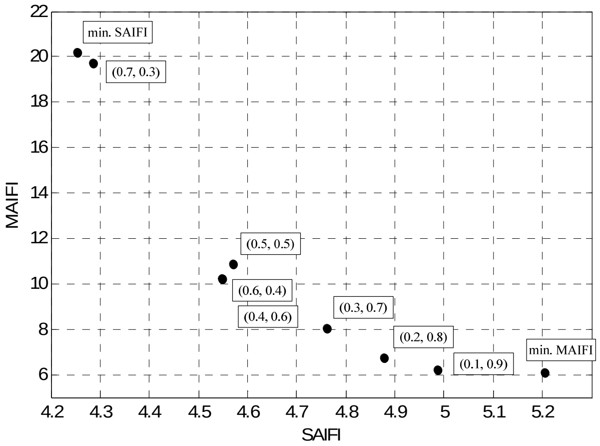

Figure 3: Solutions obtained from the minimization of SAIFI and MAIFI indices, and the NLGP model with different weights.

In the presented case study, the NLGP model comprised 169 constraints and 155 variables. As nearly all optimal solutions are usually found in the first minutes of solver execution [7], we limited the BARON solver CPU execution time to 5 minutes.

5 CONCLUSION

This paper presented a methodology to improve distribution systems reliability while establishing the trade-off between sustained and momentary interruptions-related indices. Nonlinear models were developed for SAIFI and MAIFI indices that accurately reproduce the protection system response to faults, taking into account the protective devices locations and reclosing schemes used in the substation breaker and line reclosers, fuse saving and fuse blowing. The NLBP models were solved independently to determine the lower bounds for the reliability indices, stated as goals to a NLGP model. A case study considering a real distribution feeder has shown that determining types and locations of protective devices, and a better overcurrent protection scheme to be employed in protective devices with reclosing capabilities can greatly reduce the number of customers affected by both temporary and permanent faults and thereby, minimize the distribution reliability indices.

APPENDIX

Section	λ	γ	N	Section	λ	γ	N
1	0,544	0,476	0	27	0,306	0,162	80
2	0,125	0,095	0	28	1,470	0,630	120
3	0,028	0,018	0	29	0,224	0,119	93
4	0,108	0,084	55	30	0,736	0,230	145
5	0,145	0,090	0	31	0,868	0,308	65
6	0,270	0,200	89	32	0,525	0,255	80
7	0,240	0,190	0	33	0,390	0,286	102
8	0,810	0,630	145	34	0,222	0,120	20
9	0,155	0,115	85	35	0,155	0,080	30
10	0,078	0,054	1	36	0,031	0,010	0
11	0,444	0,348	200	37	0,725	0,375	65
12	0,340	0,290	2	38	0,960	0,384	50
13	0,320	0,250	55	39	0,256	0,120	1
14	0,048	0,036	0	40	1,050	0,450	220
15	0,609	0,493	55	41	0,972	0,459	95
16	0,810	0,540	57	42	1,020	0,660	125
17	0,340	0,306	105	43	2,325	1,116	167
18	0,338	0,247	243	44	1,015	0,595	141
19	0,520	0,400	147	45	0,336	0,204	21
20	0,392	0,210	47	46	0,660	0,320	93
21	0,280	0,210	107	47	0,198	0,153	106
22	0,116	0,056	30	48	0,442	0,325	90
23	0,460	0,322	117	49	0,377	0,195	17
24	1,360	0,600	135	50	1,700	0,800	145
25	0,189	0,126	95	51	0,620	0,300	67
26	0,450	0,240	50				

Table 3: Permanent (λ) and temporary (γ) failure rates, and number of customers (N) in each section of the test feeder.

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